National Aeronautics and Space Administration

Transformational Tools and Technologies (T^3) Project

Application Table: A Bridge Connecting the Designing "With-The-Material" and "The-Material"

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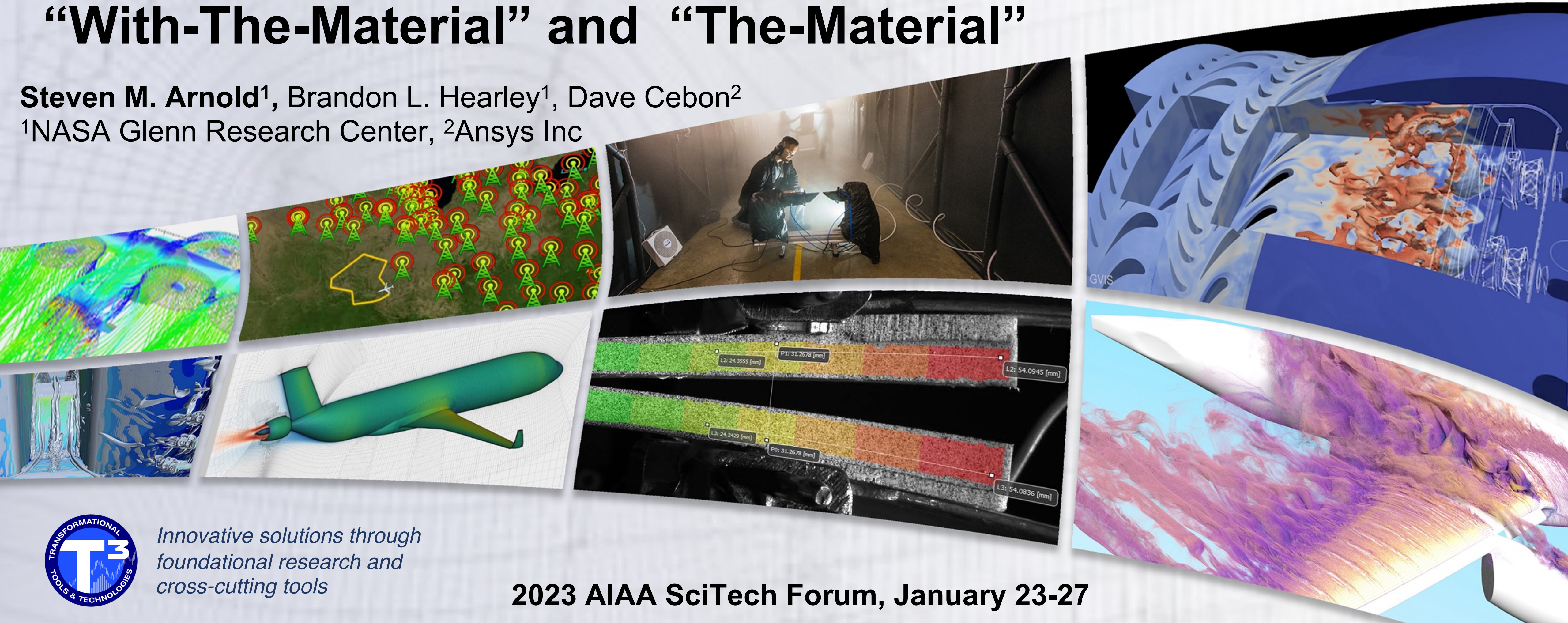
[1]NASA Glenn Research Center, [2]Ansys Inc



Innovative solutions through foundational research and cross-cutting tools

2023 AIAA SciTech Forum, January 23-27

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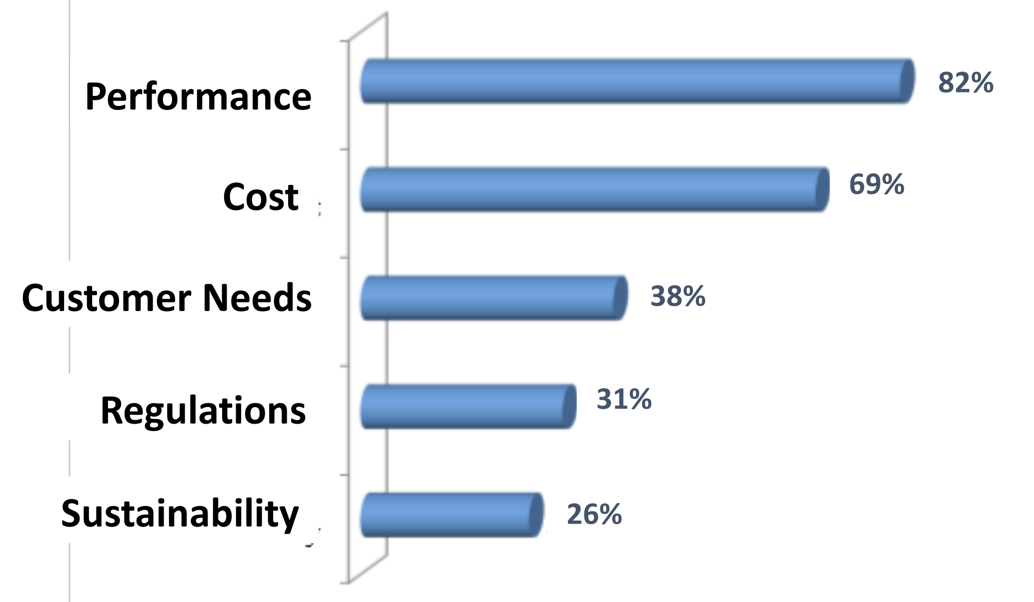
Outline

1. Motivation and Overview of the Application Table
2. Application Table Schema
   - Demonstrate the attributes through a blade-disc-rotor assembly
3. The Role of the Application Table in ICME
4. Conclusion/Summary

Rapid Material Innovation Essential For Top Performing Organizations

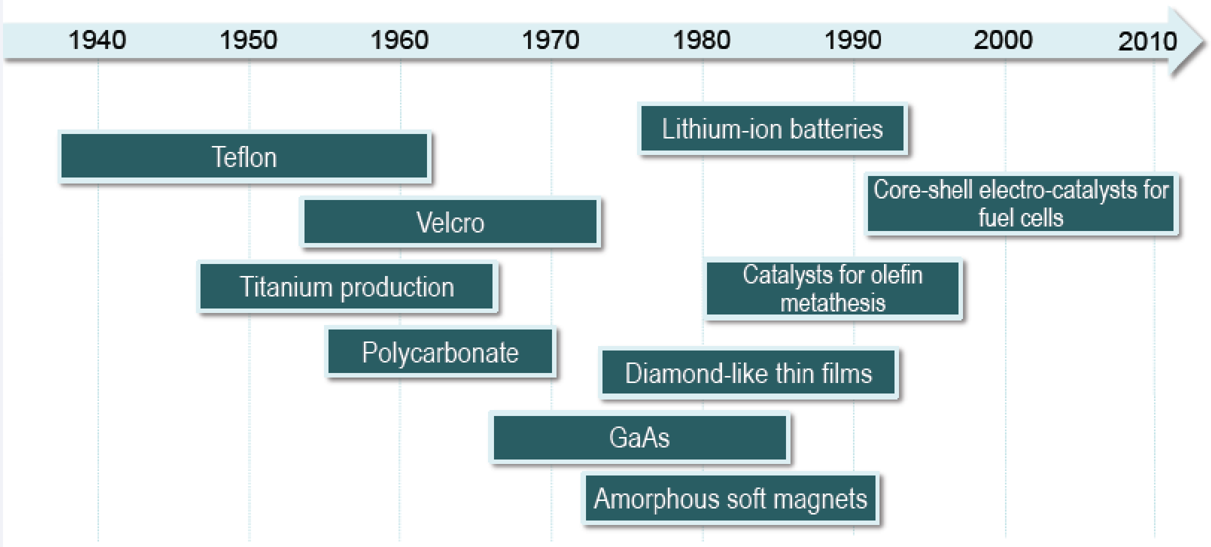
Top Performing Organizations - rate **New Materials** as one of **THE MOST IMPORTANT** factors in meeting their innovation goals.



Top Drivers for New Materials

Data taken from; "How to Empower R&D and Engineering Teams to Innovate with New Materials", Tech Clarity Inc, 2016.

Historical Material Development Time Unfortunately Measured in Decades

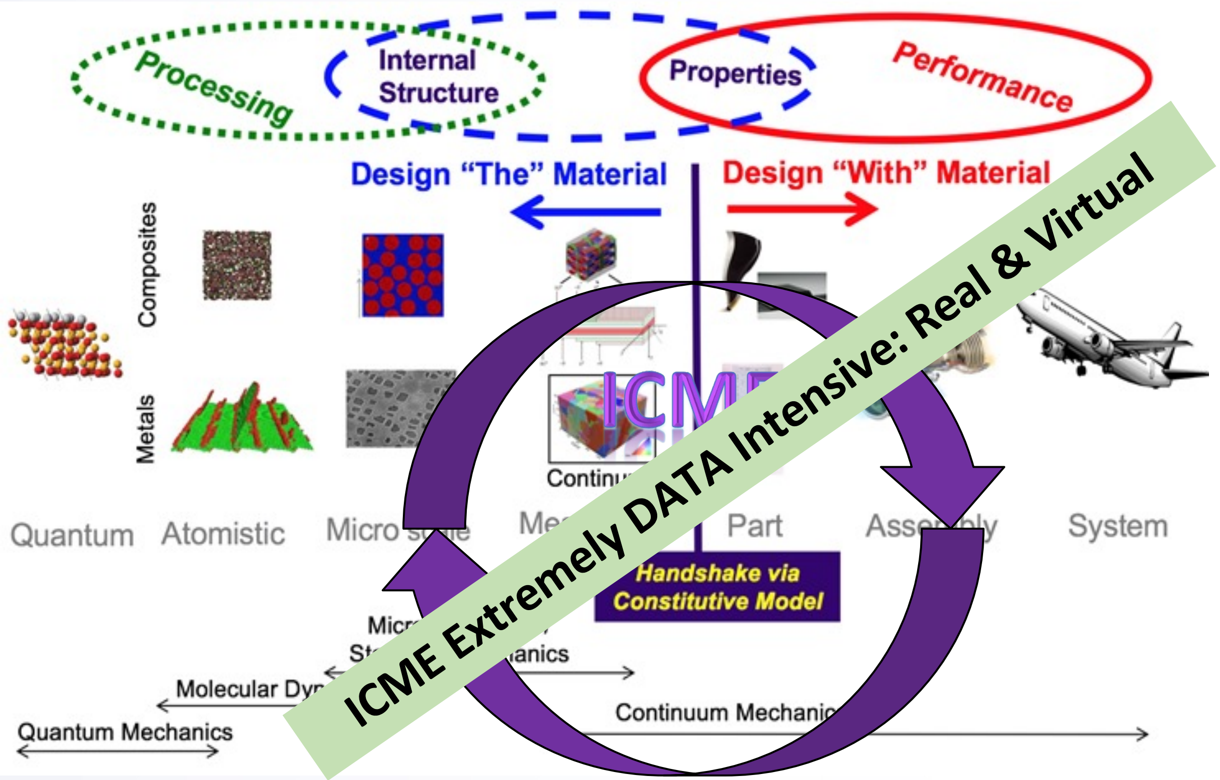


After Gerd Ceder (MIT); materials information from T. W. Eagar and M. King, Technology Review 98 (2), 42 (1995). Catalysis information from R. Schrock et al. and R. Adzic et al.

Recently, Prof. Olsen demonstrated that if **potentials are known** for material class, material development can be shortened to 3-5 years

Integrated Computational Materials Engineering (ICME) Enables Innovation

- **ICME** enables the design of “fit-for-purpose” materials
  - Requires linking experimentally validated materials models at multiple length scales
  - Requires understanding processing-structure-properties-performance relationships
  - Requires fusing of multidisciplinary information (material science vs structural engineering viewpoint)
- Traditional engineering has been split between two paradigms
  - “Design with the Material” – Structural
  - “Design the Material” – Material



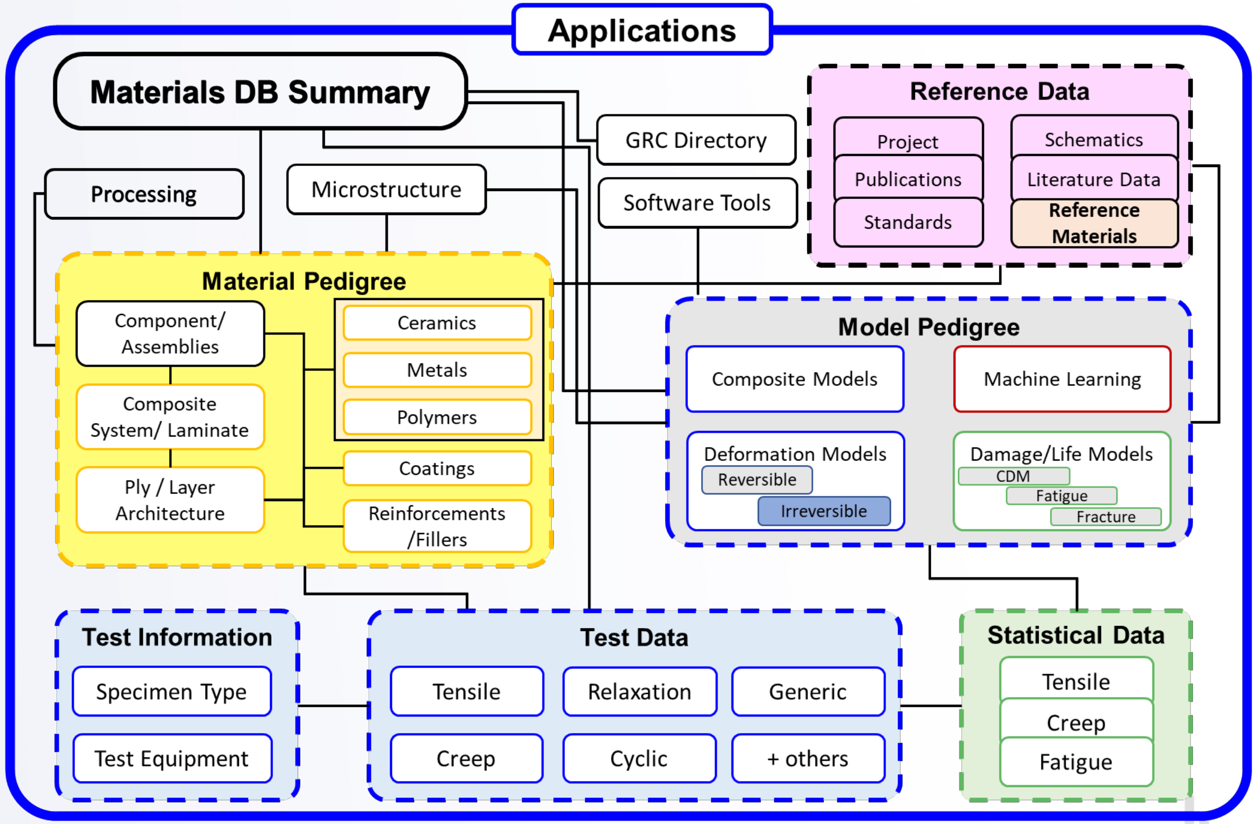
Application Table bridges the “Designing The-Material” and “Designing With-the-Material” Paradigms

Acts as the <u>*conductor*</u> *for the ICME process*

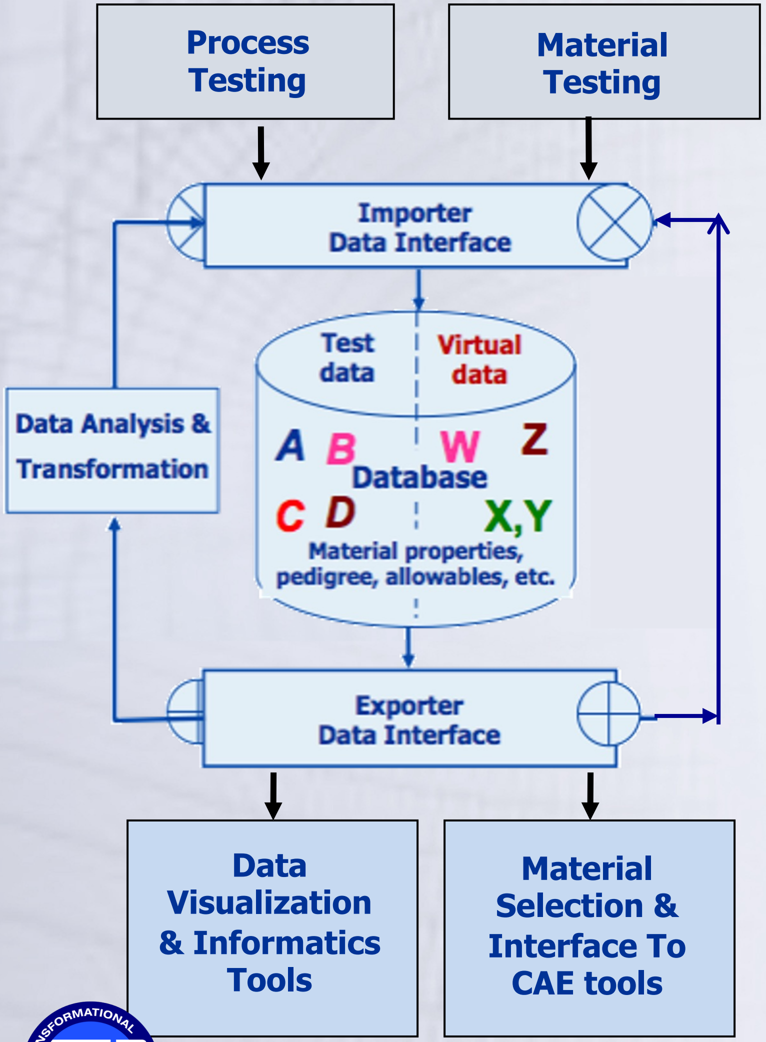
NASA GRC's ICME Schema

Application Table takes center stage as central location for:

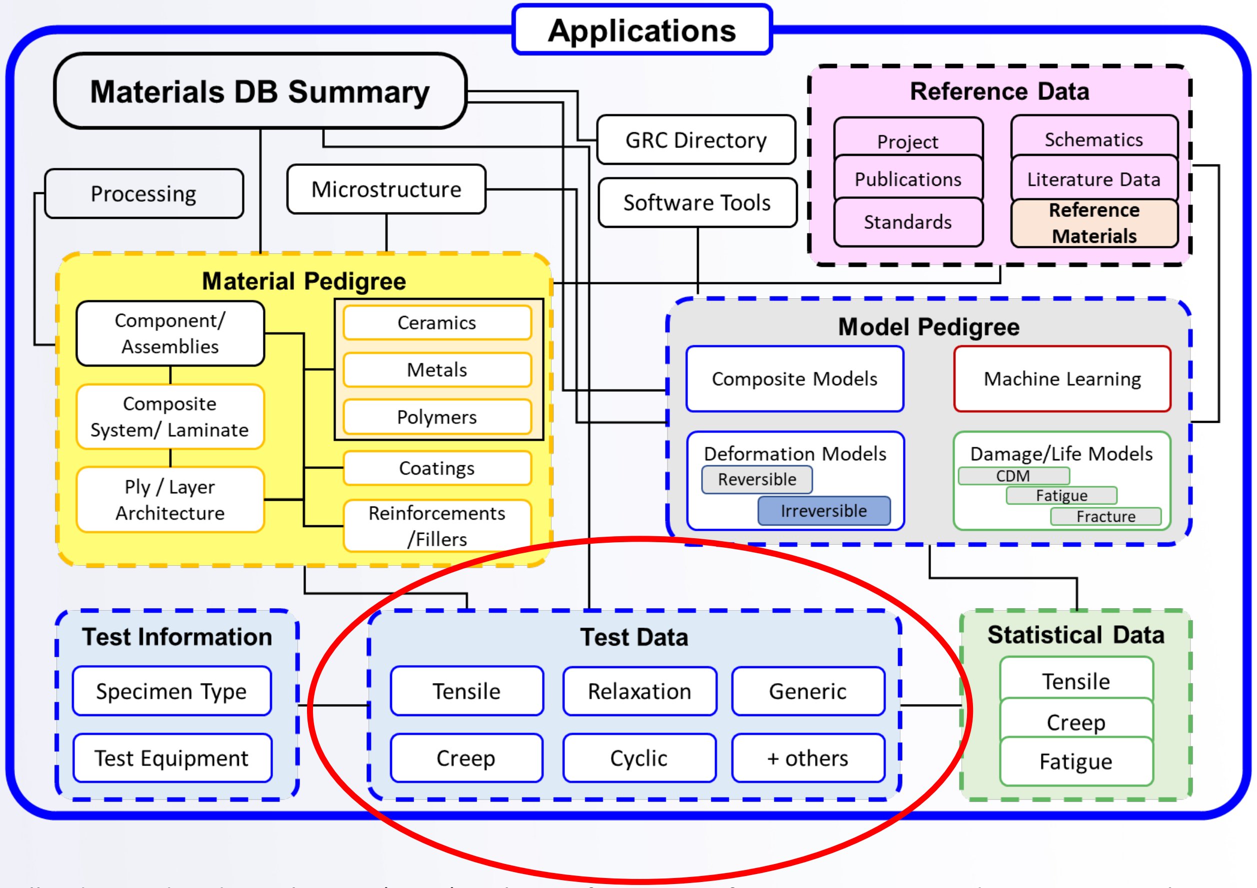
- Storing material and application performance requirements and criteria
- Providing unique location to link CAD/PLM/SDM information to materials information
- Orchestrating material selection and/or "fit-for-purpose" design
- Storing spatial and temporal information on application microstructure, residuals, damage, etc.
- Maintaining **Digital Thread and material Digital Twins**



Key To Making ICME & Virtual Testing a Reality Is Coupling Between Testing, Modelling and Application



To accomplish this introduced Model, Microstructure, Software Tools and Application Tables

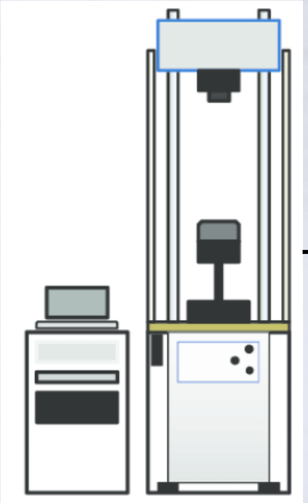


Arnold, S.M., Holland, F. and Bednarcyk, B.A.; (2014). Robust Informatics Infrastructure Required For ICME: Combining Virtual and Experimental Data, **55th AIAA/ASMe/ASCE/AHS/SC Structures**, Structural Dynamics, and Materials Conference, National Harbor, Maryland, 13 - 17 January **2014, AIAA-2014-0460**

Arnold, S. M., et. al (2015). ; "Microstructural Influence on Deformation and Fatigue Life of Composites Using the Generalized Method of Cells", **56th AIAA/ASMe/ASCE/AHS/SC Structure** AIAA SciTech 2015, ICME Special Session, Kissimmee, FL, **2015; AIAA 2015-0202**

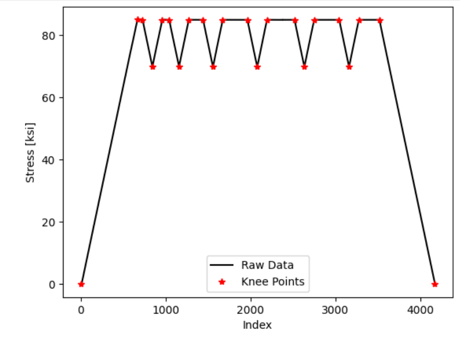
Automatic Data Analysis and Database Placement Via APIs

Raw Machine Data

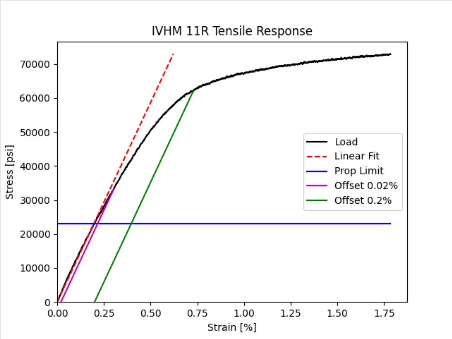


User Defines:
- Material
- Specimen Geometry

Python Data Reduction and Analysis Tool



Segment data into load stages



Perform Data Analysis based on Test Type

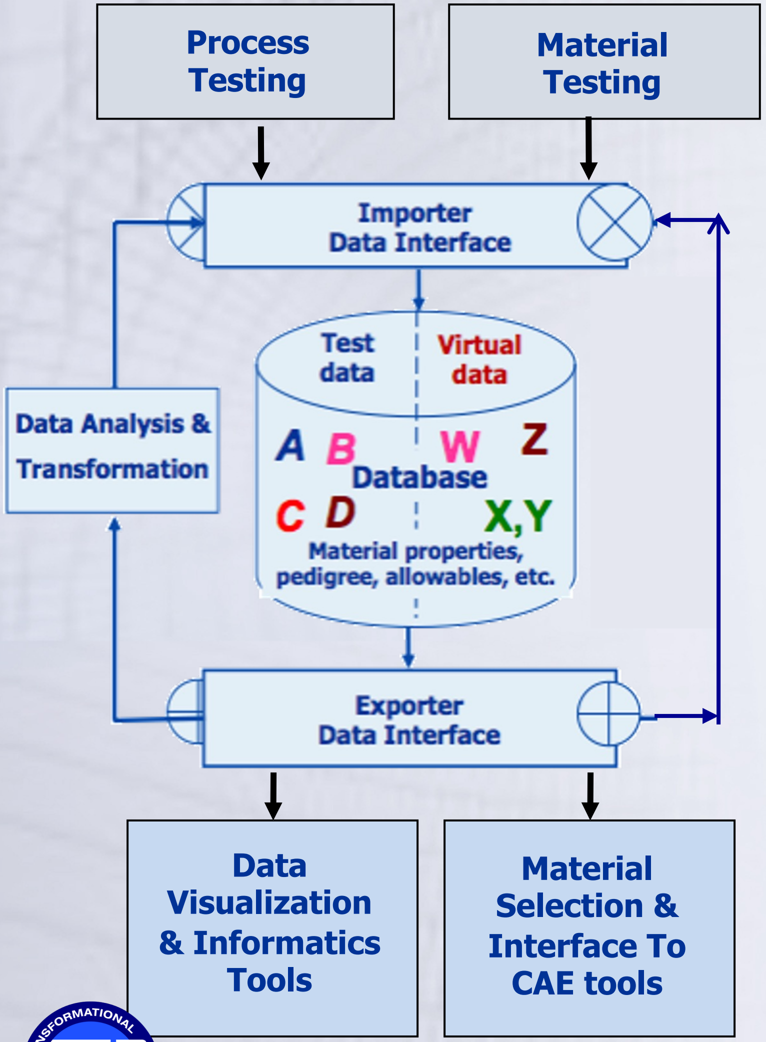
Determine Granta Record Properties
- Table (Tensile, Generic, etc.)
- Folder Placement
- Raw Data (Test Curves)
- Calculated Attributes (E, ν, etc)
- Links to Test Equipment Used
- Links Material Pedigree

Test Data
- Tensile
- Creep
- Relaxation
- Cyclic
- Wear
- Generic
- + others

Write record to Granta DB

Benefits:
- Consistent and significant data analysis/reduction
- Ease of importation of data with maximum automation included

Key To Making ICME & Virtual Testing a Reality Is Coupling Between Testing, Modelling and Application



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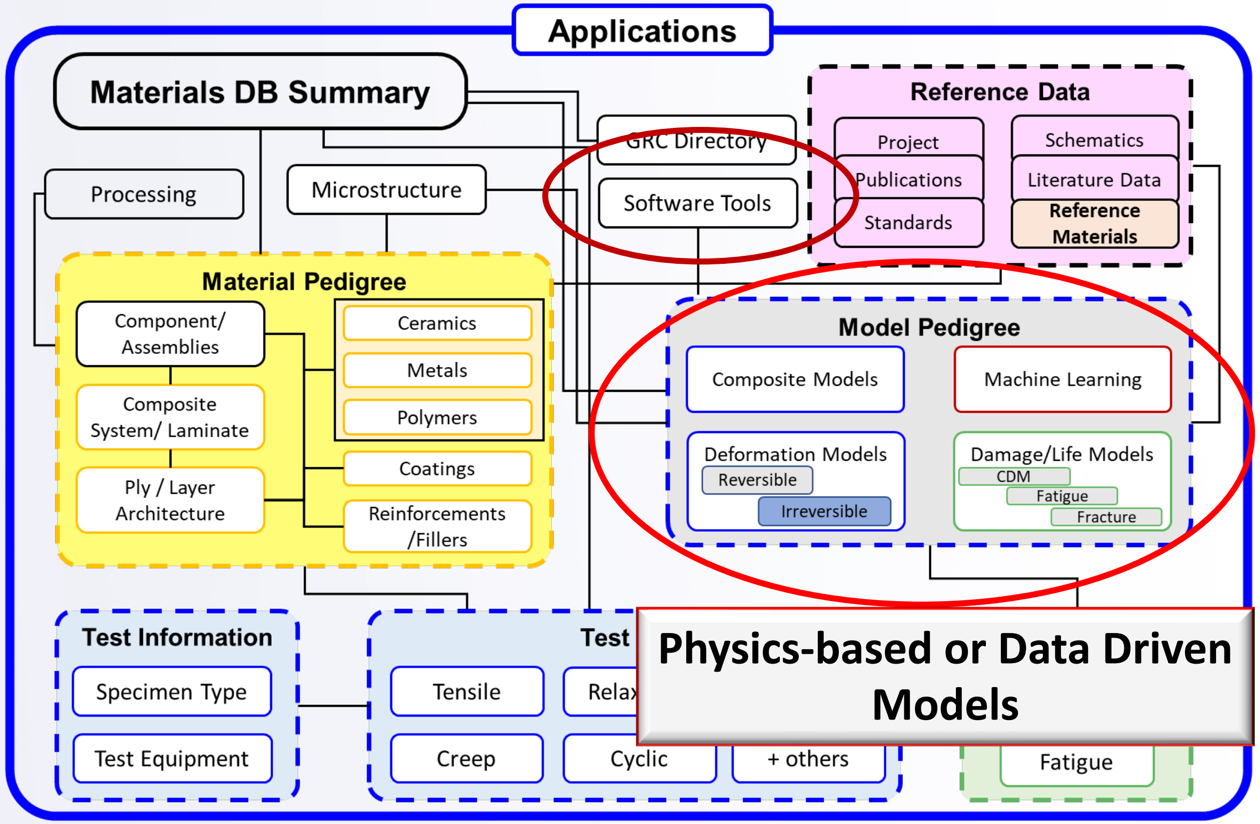


Arnold, S.M., Holland, F. and Bednarcyk, B.A.; (2014). Robust Informatics Infrastructure Required For ICME: Combining Virtual and Experimental Data, **55th AIAA/ASMe/ASCE/AHS/SC Structures**, Structural Dynamics, and Materials Conference, National Harbor, Maryland, 13 - 17 January **2014, AIAA-2014-0460**

Arnold, S. M., et. al (2015). ; "Microstructural Influence on Deformation and Fatigue Life of Composites Using the Generalized Method of Cells", **56th AIAA/ASMe/ASCE/AHS/SC Structure** AIAA SciTech 2015, ICME Special Session, Kissimmee, FL, **2015; AIAA 2015-0202**

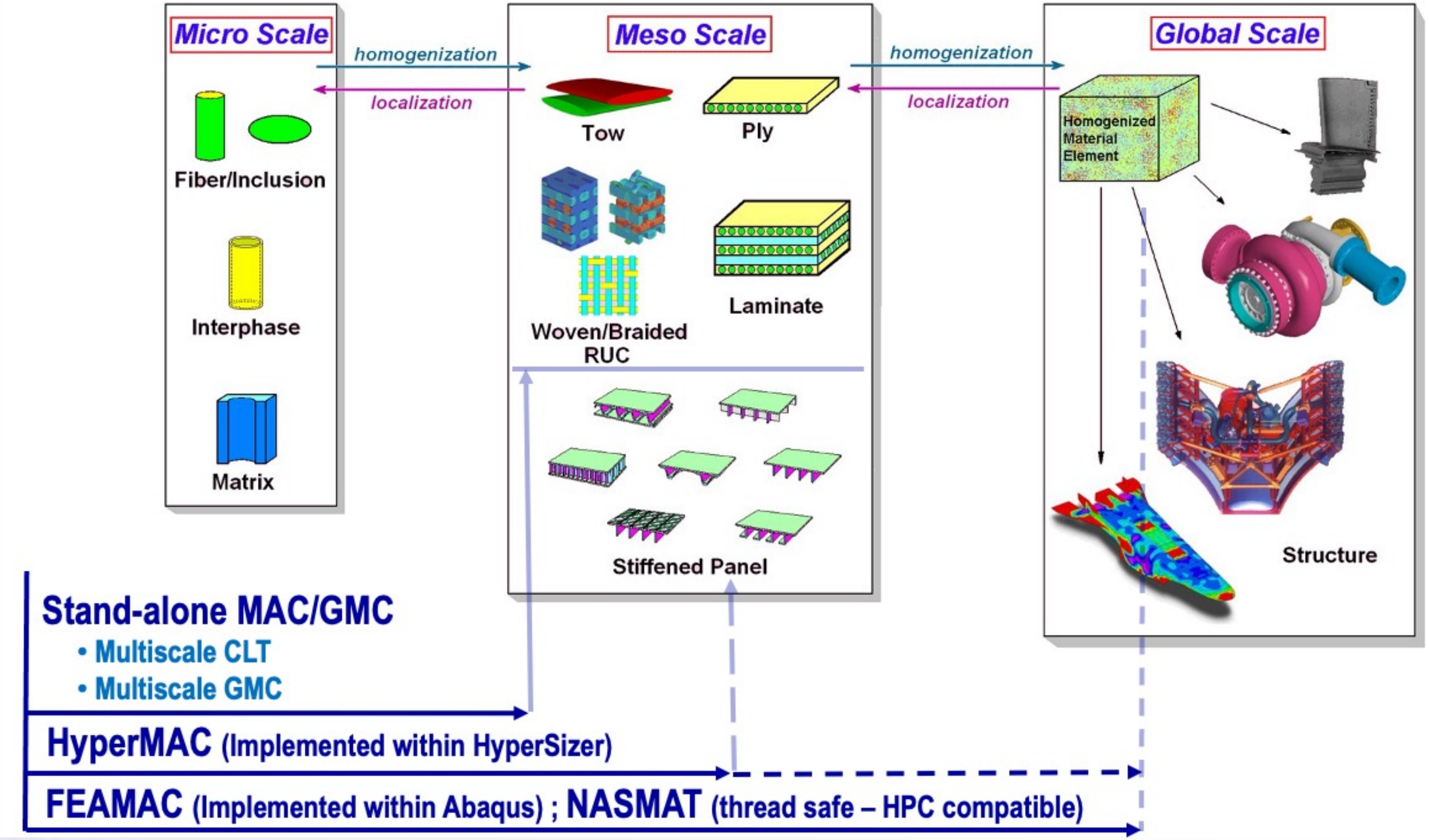
Illustration of Multiscale Database Management in ICME

Design **the** material | Design **with the** material

Multiscale Toolset: ImMAC suite

Nanoscale

- Nanoparticles /fillers
- Resin chemistry characterization
- Molecular Dynamics simulations



Digital Twin / Digital Thread for material

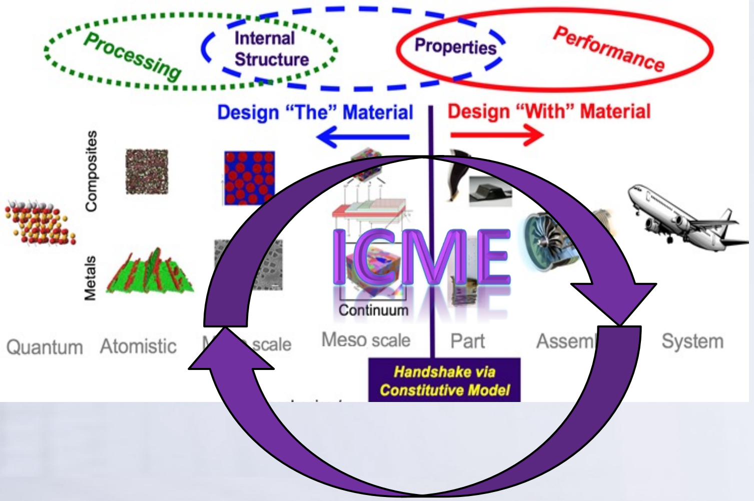
Aboudi, J., Arnold, S.M., and Bednarcyk, B.A. (2013) ***Micromechanics of Composite Materials: A Generalized Multiscale Analysis Approach***, Elsevier, Oxford, UK., pp 1-984.

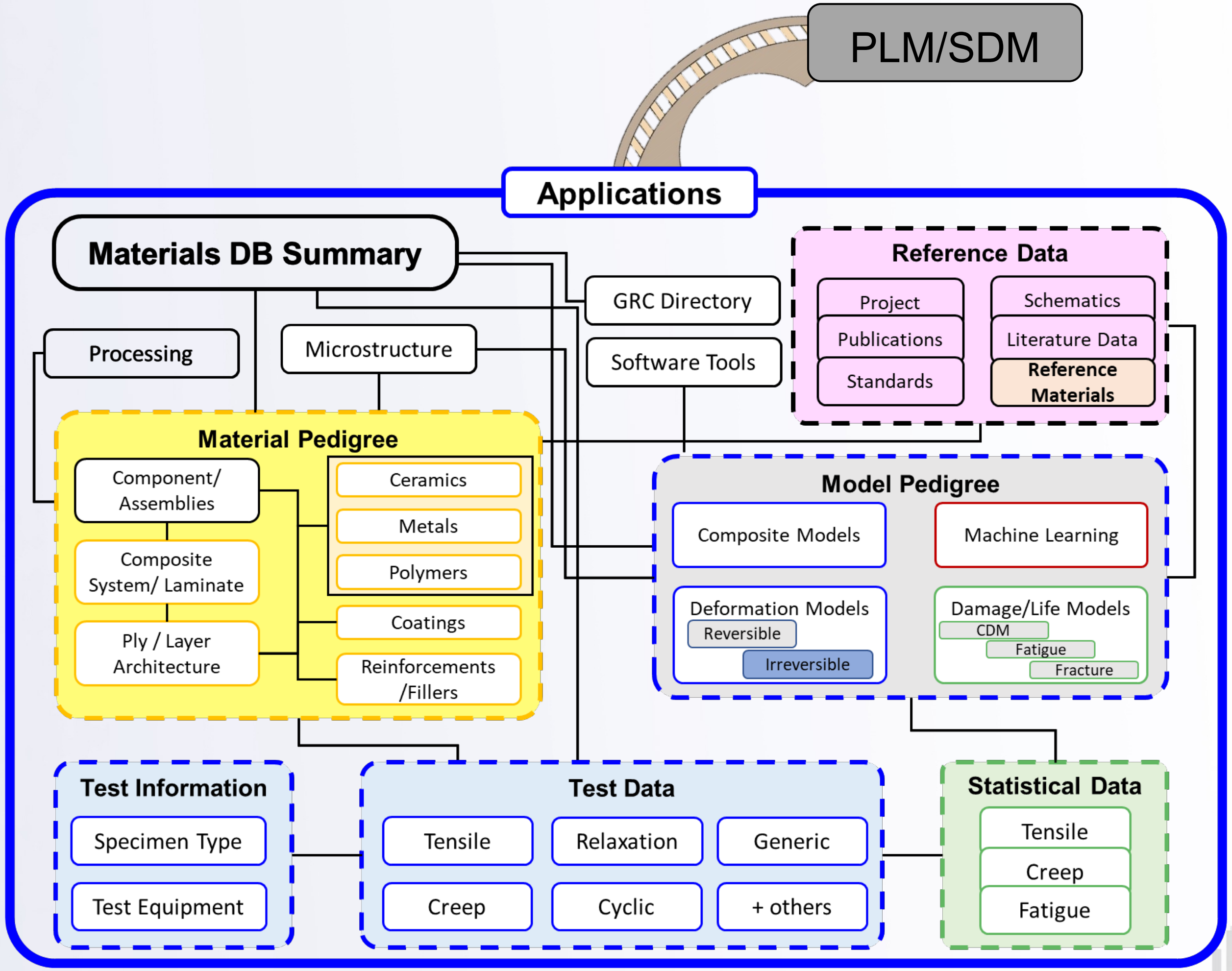
Aboudi, J., Arnold, S.M., and Bednarcyk, B.A. (2021) ***Practical Micromechanics of Composite Materials***, Elsevier, Oxford, UK

NASA GRC’s ICME Schema

Acts as the conductor for the ICME process

Application Table bridges the “Designing The-Material” and “Designing With-the-Material” Paradigms

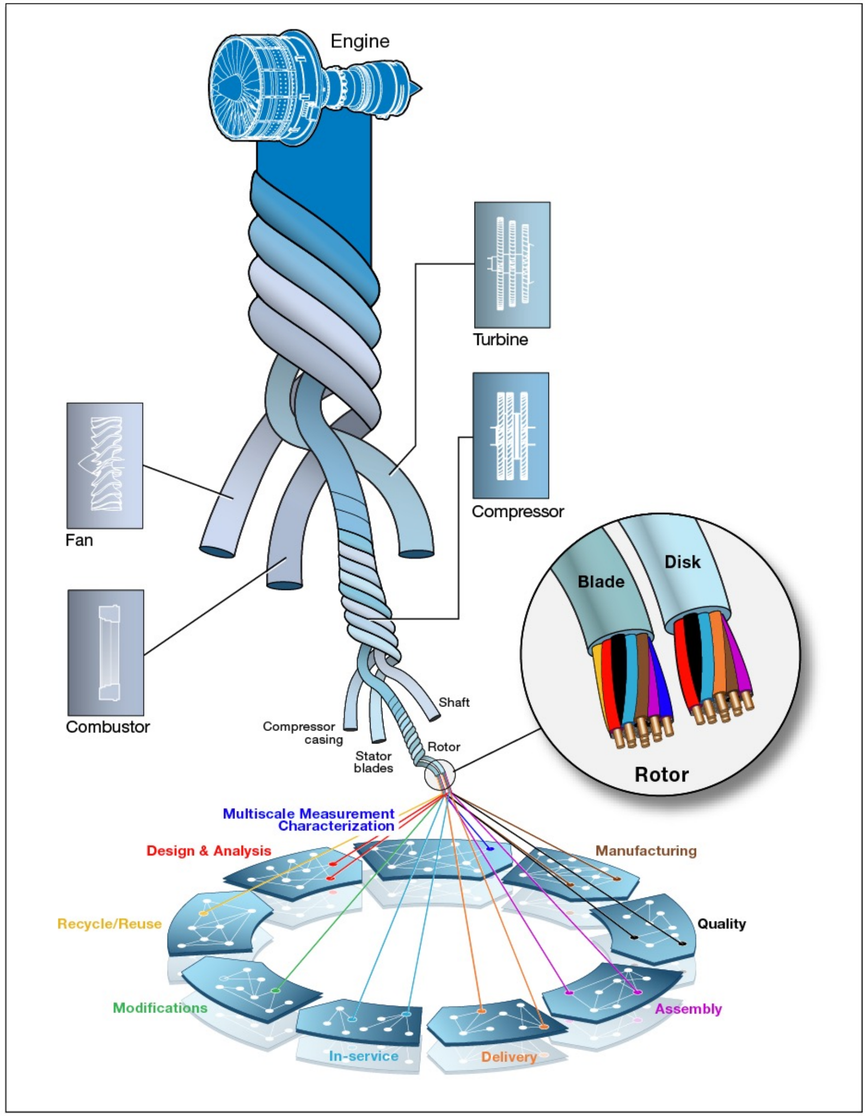




Application Table Able to Store System of Systems

- System of system storage philosophy
  - Both **assemblies, sub-assemblies, parts** are stored in individual records
  - (Sub) Assembly records relate part records in the *Application Table* to the application define (sub) assembly level specifications/requirements
    - Recursive linking allows maintenance of a system of systems
  - Part records relate material information in *other tables* to the application and define part level specifications/requirements

➢Orchestrates the interdependence between material and structural performance enabling optimal design



Application Table Schema

- Attributes and Layout defined to handle any type of application or requirements
  - Nine major categories specified with associated attributes
    - Associated requirements are dispersed throughout three major category (Geometric, Performance, Material)
    - Can be application-based or spatial (allow definition of design points)
    - Contains evaluation criteria (Analysis Performed and results (Scorecards and Readiness Levels) for the requirements
- Granta MI Tabular attribute type used extensively due to its flexibility and generality
  - Significant number of additional attributes associated with each column of a tabular attribute
  - Each row can represent different specifications

Attribute	Type
General Information	
Application Name	STXT
Application Description	LTXT
Data Ownership	DCT
Data Ownership (Other)	STXT
Distribution Category	DCT
Funding Organization	STXT
Performing Organization	STXT
Project Name	STXT
Project Code	STXT
Project Notes	LTXT
Point of Contact	TABL
Geometric/Manufacturing Requirements	
Owner Information	TABL
Surface Area	RNG
Volume	RNG
Bounding Box Dimmensions	LTXT
CAD/CAE Link	HYP
Manufacturing Process	DCT
Manufacturing Process (Other)	STXT
Geometric Schematic Time History	TABL
Geometric Description	TABL
Coordinate System Definitions	TABL
Design Points / Points of Inerest*	TABL
Geoemtric Notes	LTXT
Manufacturing Requirements*	TABL
Part Yield	RNG
Surface Treatment	DCT
Manufacturing Notes	LTXT
Microstructure Profile	TABL
Performance Requirements	
Weight	RNG
Life	RNG
Cost	RNG
Risk	DCT
Storage Energy	RNG
Ultimate Strength	RNG
Performance Standards*	TABL
Mechanical Requirements*	TABL
Thermal Requirements*	TABL
Environmental Requirements*	TABL
Other Performance Requirements*	TABL
Performance Notes	LTXT
Form/Fit/Function Notes	LTXT

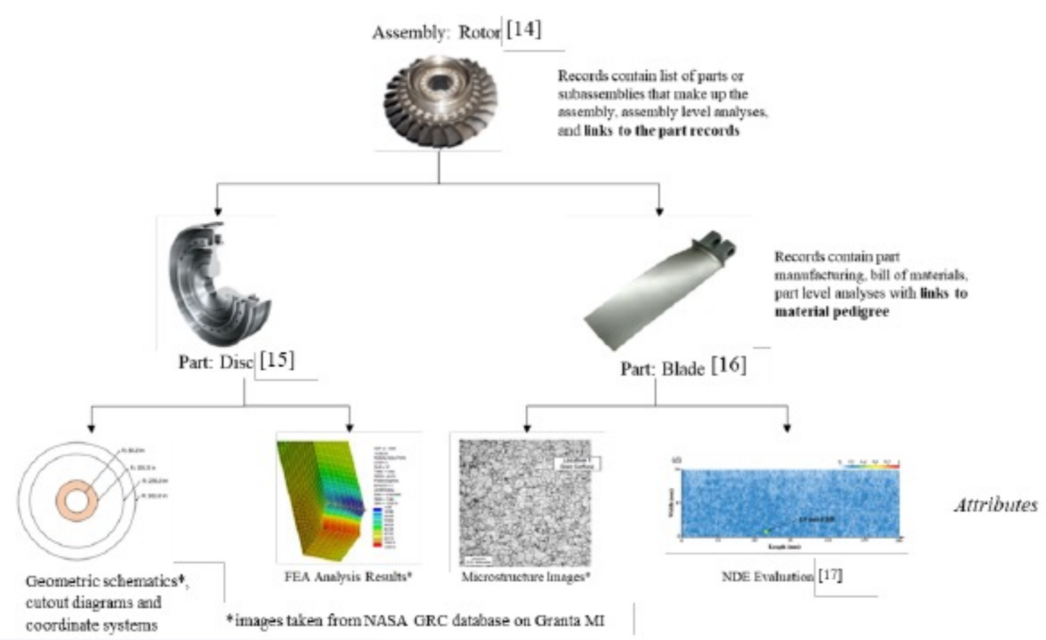
Attribute	Type
Analyses Performed	
Analyses Performed	TABL
Analyses Performed (Subcomponents)	TABL
Analyses Profiles	TABL
Load Profiles	TABL
Analyses Range Definitions	TABL
Failure Mechanism/Modes	
Failure Mode and Effect Analysis	TABL
Material Selection/Requirements	
Material Requirements*	TABL
Part List	TABL
Bill of Materials*	TABL
Software Tools Used**	TABL
Selection Criteria	FILE
Property File	FILE
Material Selection Assumptions	LTXT
Inspection	
Inspectability Notes	LTXT
Evaluator	TABL
NDE Method	DCT
NDE Geometry	TABL
Equipment	TABL
Examination	TABL
Calibration	TABL
Testing Parameters	TABL
NDE Images	TABL
NDE Comments	LTXT
NDE Information	FILE
Scorecards	
Requirements Scorecard*	TABL
Risk Scorecard*	TABL
Readiness Levels	
Technology Readiness Level (TRL)	DCT
Manufacturing Readiness Level (MRL)	DCT
Integration Readiness Level (IRL)	DCT
System Readiness Level (SRL)	DCT

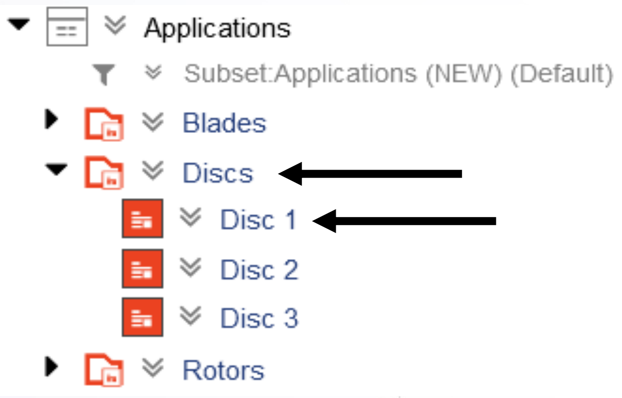
* Changed with feature request
** Removed with feature request

DCT	Discrete Text (speificied choices)
FILE	Allows the association of any file type to a given record
HYP	Hyperlink to a web address
IMG	Allows the association of any image format to a given record
LTXT	Long Text Field
PNT	Point Value
RNG	Range Variable
STXT	Short Text Field
TABL	Tabular Attibute

Demonstration Through Example: Rotor Assembly

- Rotor Assembly
  - Define *Application Table* records for **parts** (e.g., disc, blade), and **assemblies** (e.g., rotor), where the part records are *linked* to the assembly records
- General Folder Organization
  - Each application has a **generic record** that contains typical requirements, approved materials, etc. for the application ***in general***
    - Use this information in the early stages of design
  - **Records within** each generic record relate to specific applications/parts to be produced
    - Use this record as a part of the **digital thread** for the actual part
- Examine 6/71 attributes to enable one to get a feeling for breadth of information contained within the Application Table





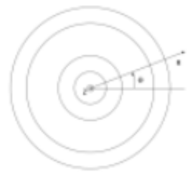
Geometric/Manufacturing Requirements

Design Points/Points of Interest

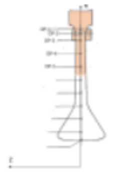
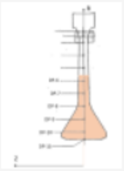
- Define coordinate systems through a tabular attribute to allow for multiple
  - Define rotation matrices between systems
  - Rotation matrix is assumed from current row to row above
- Design Points/Points of Interest used for spatial requirements
  - User defines an ID, the component / zone the point lies in, its position in a coordinate system, and a schematic
  - Currently assuming all points are defined on its nearest above schematic to avoid repeating the same schematic for each row

Coordinate System Definitions   Hide table

Save as CSV | Copy To Clipboard

Name	Schematic	Description	Rotation Matrix to Next CS
Global		Polar coordinate system	

Save as CSV | Copy To Clipboard

Point ID	Component / Zone ID	Schematic	Coordinate System	R (in)	Θ (°)	Z (in)
DP-1	D1-1		Global	86.0	0	0
DP-2	D1-1		Global	102	0	0
DP-3	D1-1		Global	127.0	0	0
DP-4	D1-1		Global	152	0	0
DP-5	D1-1		Global	178	0	0
DP-6	D1-2		Global	203	0	0
DP-7	D1-2		Global	229	0	0
DP-8	D1-2		Global	254.0	0	0
DP-9	D1-2		Global	279	0	0
DP-10	D1-2		Global	293	0	0
DP-11	D1-2		Global	302	0	0

Performance Requirements

Application-Specific Requirements

- Use tabular attributes for application specific requirements
  - Users can define requirements as target values (spatially dependent) or as logical (Y/N)
    - Use LTXT column types for full flexibility
  - Separated into 4 categories: <u>Mechanical</u>, Thermal, Environmental, Other

Mechanical Requirments Hide table

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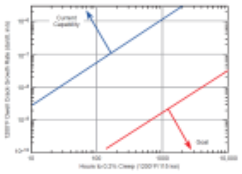
Name	Design Point ID	Image	Description	Functional Data Pairs	Target	Units	Equation (Y/N)?
Creep vs. Crack Growth			The part must operate in the defined Hours to 0.2% Creep vs 1200	[0 1 2 3 4 5 6 7 8 9 10] [0 10 20 30 40 50 60 70 80 90 100]			No
Radial Deflection	DP-1 DP-2 DP-3 DP-4 DP-5 DP-6 DP-7 DP-8 DP-9 DP-10		The maximum allowed radial deflection as a function of position.		0.698 0.746 0.829 0.935 1.093 1.260 1.423 1.589 1.763 1.860	mm	No

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Analyses Performed

Part Level (Disc)

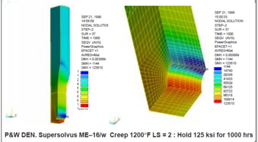
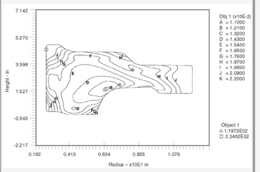
- Store a **summary** of the analyses performed and results with links to the PLM/SDM

Analyses Performed Hide table

Component / Zone ID	Analysis ID	Analysis Description	Analysis Type	Date Performed	PLM/SDM/CAE Link
D1	D1-1A	Creep at 1200°F, Hold at 125 ksi for 1000 hrs	Mechanical - Static	Monday, October 3, 2022	D1-1A_Creep_125ksi.wbpj
D1	D1-2A	Effective strain during 60 sec dwell	Mechanical - Static	Friday, October 7, 2022	D1-2A_Dwell_60s.wbpj
D1	D1-3A	Cooling Rate (°F/min) during Quenching	Thermal	Tuesday, October 11, 2022	D1-3A_Cooling_Quench.wbpj

Summary of what analyses were done

Analyses Profiles Hide table

Analysis ID	Component ID	Design Point ID	Analyzed Profile	Design Point Results - Values	Design Point Results - Property	Design Point Results - Units
D1-1A	D1-1	DP-1		252.6	Max. Principle Stress	MPa
	D1-1	DP-2		287.4		
	D1-1	DP-3		321.1		
	D1-1	DP-4		385.9		
	D1-1	DP-5		387.2		
	D1-2	DP-6		395.5		
	D1-2	DP-7		400.1		
	D1-2	DP-8		402.8		
	D1-2	DP-9		435.1		
	D1-2	DP-10		467.1		
D1-2A	D1-1	DP-1		2.20	Effective Strain (R-Direction)	%
	D1-1	DP-2		2.09		
	D1-1	DP-3		1.98		
	D1-1	DP-4		1.76		
	D1-1	DP-5		1.54		
	D1-2	DP-6		1.52		
	D1-2	DP-7		1.67		
	D1-2	DP-8		1.84		
	D1-2	DP-9		1.99		
	D1-2	DP-10		2.05		

Summary of the critical results. Design Point Values is LTXT to enable concise definition for each Design Point

Analyses Performed

Assembly Level (Rotor)

- Analyses Performed and Analyses Profile attributes are defined in the Application Table for that part or assembly
- For assembly records, an additional attribute – Analyses Performed (Subcomponents) – shows the analyses that have been performed on the subcomponents
  - Links to the Analyses Performed attribute for the parts

Rotor 1

Analysis Results

Analyses Performed (Subcomponents) Hide table

Part Record	Component / Zone ID	Analysis ID	Analysis Description	Analysis Type	Date Performed	Analyst Name
Blade 1	B1	B1-1A	Stress Analysis at operating temperature	Mechanical - Static	Thursday, October 13, 2022	Brandon Hearley
Disc 1	D1	D1-1A	Creep at 1200°F, Hold at 125 ksi for 1000 hrs	Mechanical - Static	Tuesday, October 11, 2022	Brandon Hearley
	D1	D1-2A	Effective strain during 60 sec dwell	Mechanical - Static	Tuesday, October 11, 2022	Steven Arnold
	D1	D1-3A	Cooling Rate (°F/min) during Quenching	Thermal	Tuesday, October 11, 2022	Brandon Hearley

Material Requirements/selection

Material Requirements

- Material Requirements list requirements for the materials to be chosen
  - Takes similar form to Mechanical, Thermal, etc. Requirement tabular in the Performance Requirements heading
  - Can be component/zone-defined or design point/point of interest-defined

Material Requirements Hide table

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Name	Component / Zone ID	Design Point ID	Description	Target	Units
Maximum Temperature (Hub)	D1-1		Maximum operating temperature for the material	750	°C
Maximum Temperature (Tip)	D1-2		Maximum operating temperature for the material	1000	°C
Yield Stress		DP-1 DP-2 DP-3 DP-4 DP-5 DP-6 DP-7 DP-8 DP-9 DP-10	Minimum required yield stress for the material at the design point specified.	187 187 191 195 200 205 208 210 212 214	MPa

Material Requirements/selection

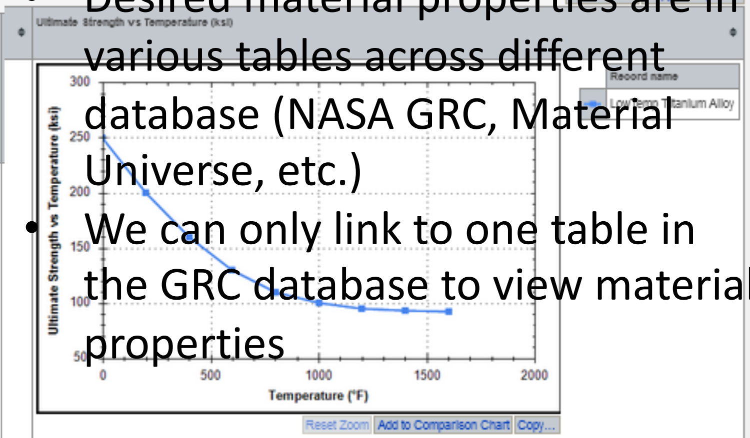
Bill of Material (BOM)

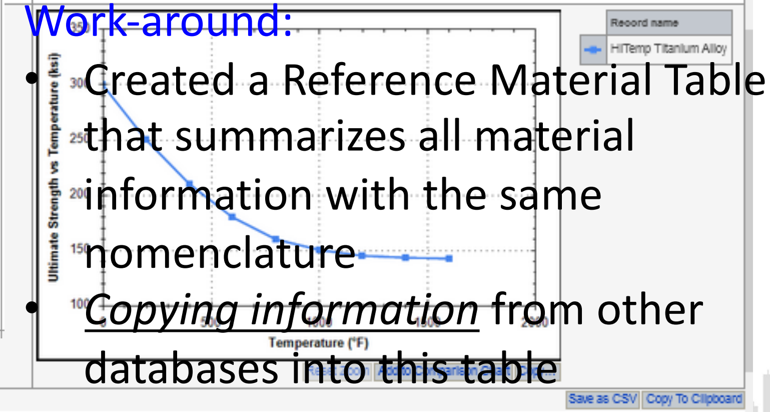
- At the part level, the Bill of Materials is populated
  - Define the *materials* used in each component/zone

Bill of Materials   Hide table

Component / Zone ID	Component Name	Material	Material Class	Density (lb/ft^3)	Maximum Temperature (°F)	Environment	Hazardous	Machinability	Weldability	Cost ($/g)	Material Accessibility	Elastic Modulus (Isotropic) (10^6 psi)
D1-1	Disc Hub Material	LowTemp Titanium Alloy	Metal	281	2500	High Temperature	No	Yes	Yes	100	Tier I	17.4

Properties viewed from the Refence Material Table





Issue:

- Desired material properties are in various tables across different database (NASA GRC, Material Universe, etc.)
- We can only link to one table in the GRC database to view material properties

Work-around:

- Created a Reference Material Table that summarizes all material information with the same nomenclature
- *Copying information* from other databases into this table

Material Requirements/selection

Parts List

- At the assembly level, the Parts List is populated
  - Define the *parts (applications)* used in the assembly

Rotor 1

Material Selection/Requirements

Part List

Hide table

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Application Name	Quantity	Weight (Each) (lbf)	Cost (Each) ($)	Life (hr)	Risk
Disc 1	1	$250 \le x \le 500$	2000	10000	Medium
Blade 1	16	5	1000	10	Low

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Links to the Application Table "Part" records

Define Quantities of Each

View properties from the Application Table part records
- No way currently to see the totals (i.e., multiple 16 * 5 to show the total blade weight)

Scorecards

Requirements Scorecards

- The Scorecards header gives a summary of the status of every requirement for the given application
  - **Issue**: Requirements could be best described as logical (Met/Not Met) or with a margin
    - Safety factor for DP 1 meets the requirement, but a value of 5 indicates overdesign and the need for material optimization
    - Whether or not the material's maximum temperature is below the operating temperature is better described logically
  - Ideally, each cell's type (PNT, LOG, etc.) could be set based on the requirement
  - **Work-around**: All types are long text

Requirements Scorecard Hide table

Requirement Type	Requirement Name	Component / Zone	Design Point 1	Design Point 2	Design Point 3	Design Point 4	Design Point 5	Design Point 6	Design Point 7
Mechanical	Creep vs Crack Growth	Met	*Could apply to the whole part or individual design points*						
Mechanical	Safety Factor		5.0	3.5	1.9	1.8	1.7	1.6	1.5
Thermal	Stress vs Temperature	Met	*Could be logical (Met/Not Met) or a margin*						
Material	Maximum Temperature		Not Met	Not Met	Met	Met	Met	Met	Met

Readiness Levels

- Summarize the application through various readiness levels
  - Provide traceability as to why we're a certain readiness levels from scorecards

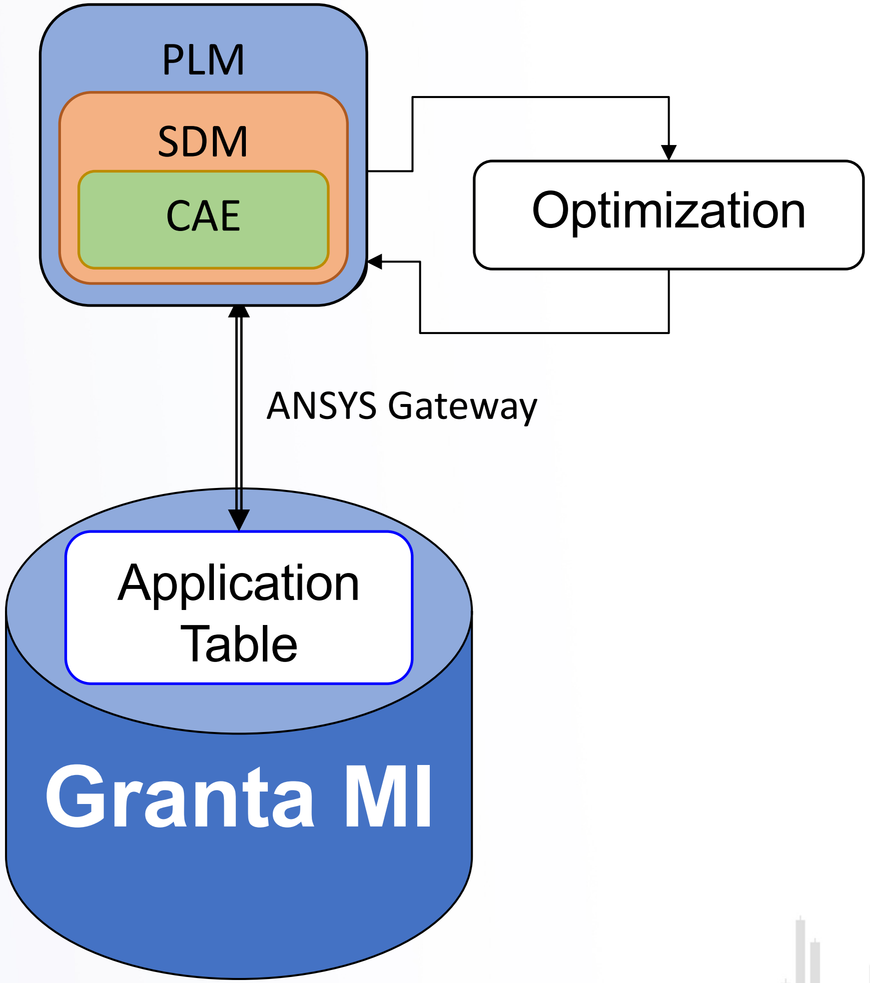
Readiness Levels	
Technology Readiness Level (TRL)	TRL 4
Manufacturing Readiness Level (MRL)	MRL 3
Integration Readiness Level (IRL)	IRL 5
System Readiness Level (SRL)	SRL 3

Integration Readiness Levels

Level	IRL Description
1	An interface between technologies has been identified with sufficient detail to allow characterization of the relationship.
2	There is some level of specificity to characterize the interaction between technologies through their interface.
3	There is compatibility between technologies to orderly and efficiently integrate and interact.
4	There is sufficient detail in the quality and assurance of the integration between technologies.
5	There is sufficient control between technologies necessary to establish, manage, and terminate the integration.
6	The integrating technologies can accept, translate, and structure information for its intended application.
7	The integration of technologies has been verified and validated with sufficient detail to be actionable.

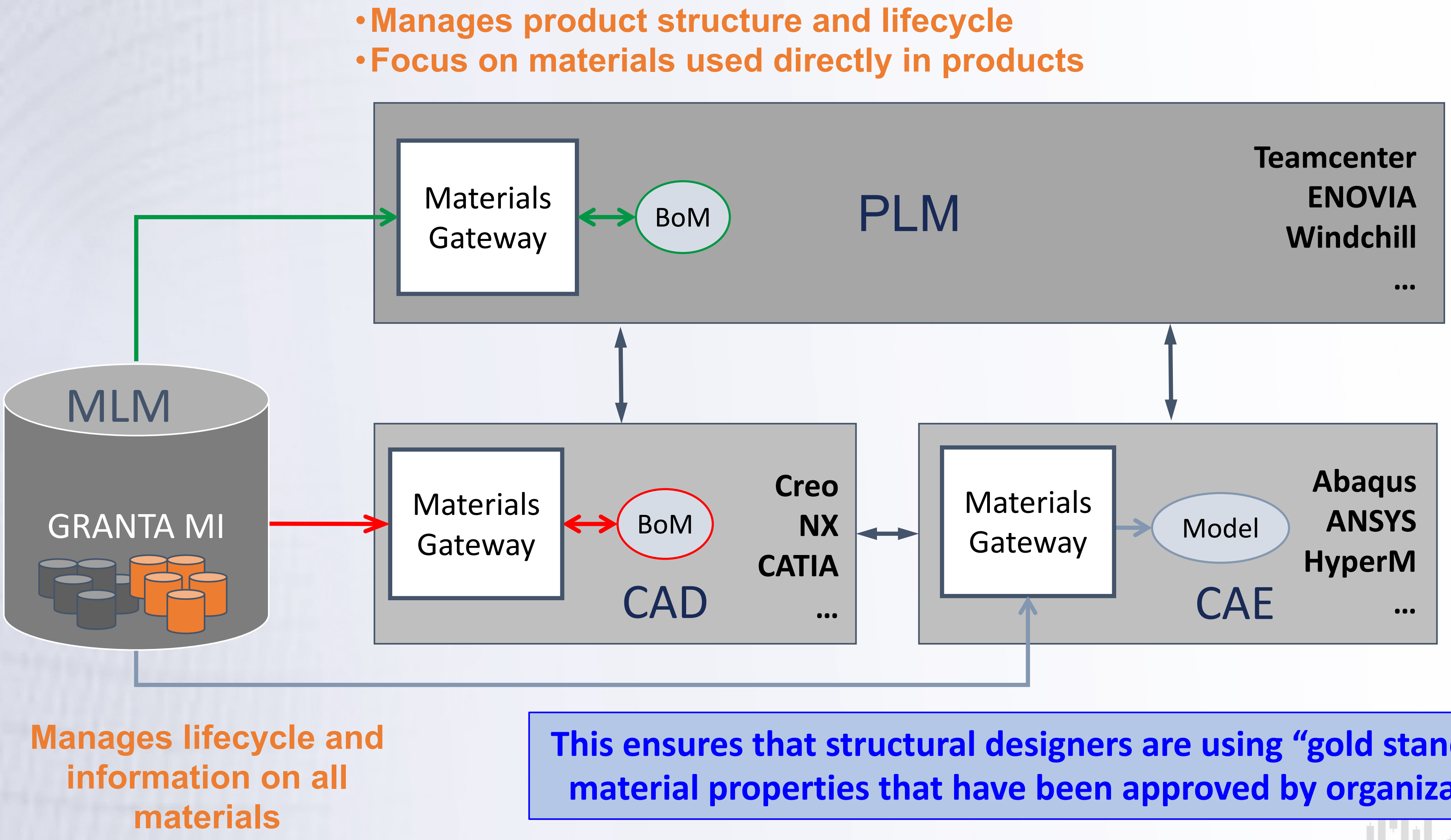
Illustration of Utilization of Application Table
Traditional Material Selection

- Select a known material based on application requirements
  - Use macroscale material properties (which incorporate all lower length scales effects)
- Iterate on the structural design until requirements in the PLM/SDM are met
  - If requirements cannot be met, select a new material



Material and Structure viewpoints are non-concurrent!

Structural Engineers Benefit From Linkage Between MLM and Engineering Application Software

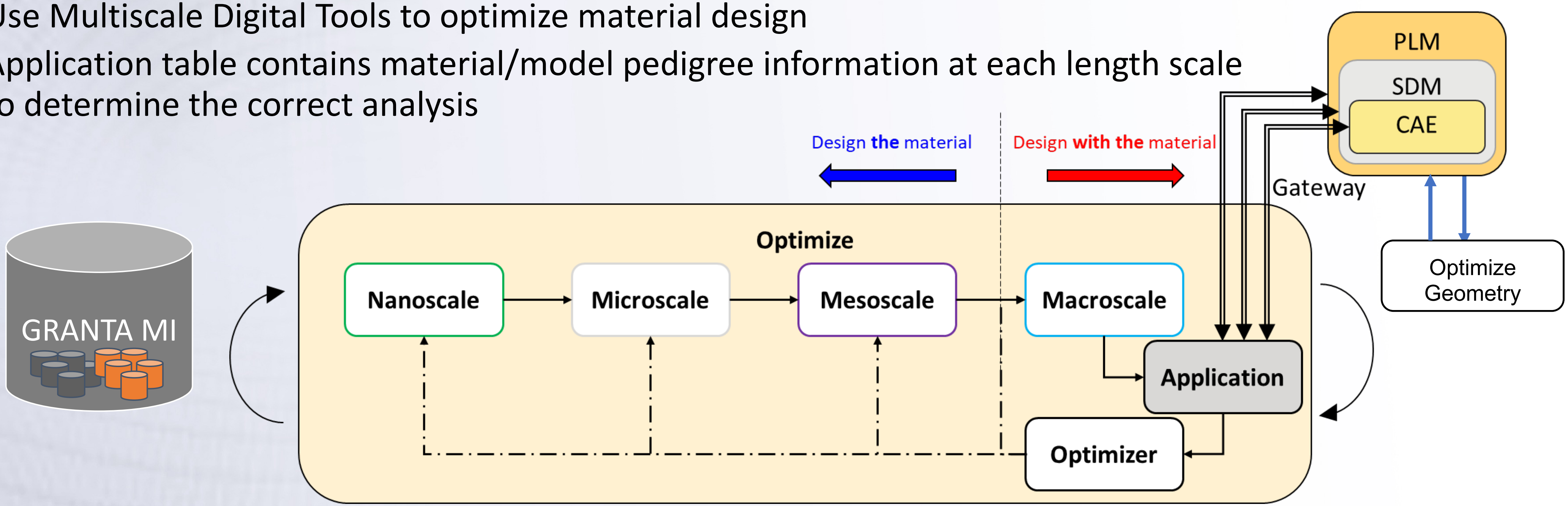


This ensures that structural designers are using "gold standard" material properties that have been approved by organization

Application Table in Orchestrating ICME

Fit-for-Purpose Material Design

- ICME Design
  - Design the material for a specific application from processing through performance (fit-for-purpose)
  - Use Multiscale Digital Tools to optimize material design
  - Application table contains material/model pedigree information at each length scale to determine the correct analysis



- Re-evaluate the requirements locally with periodic global (structural – PLM/SDM) updates

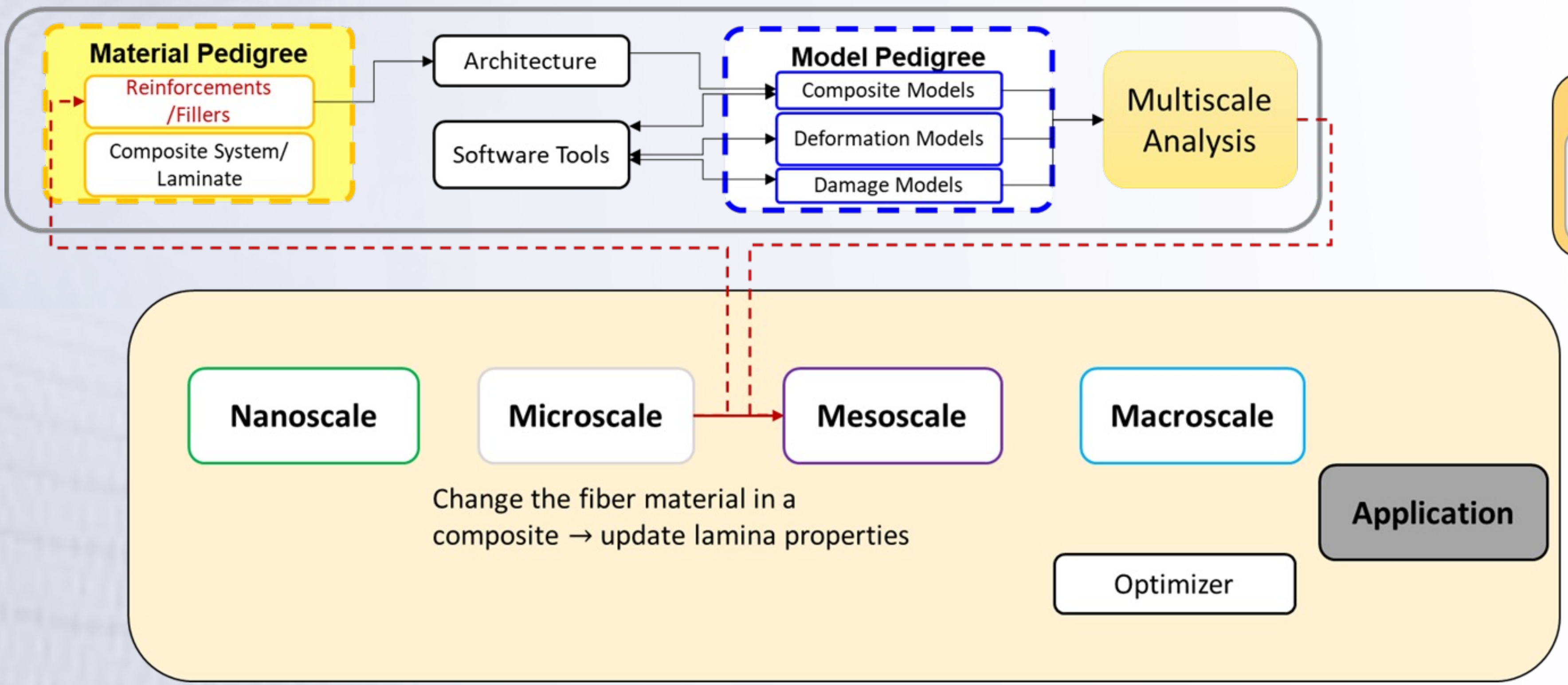
Remember the two important key words in ICME being
1) **Integrated** wherein processing histories, influence internal structure, which in turn drive properties, which then drive performance and
2) **Engineering** which signifies industrial utility!

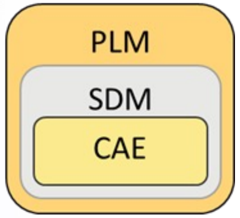
Application Table in Orchestrating ICME

Illustrate with Example in which the **fiber reinforcement of a composite material** used for a structural component is varied

- Consider changing the material characteristics at lower scales
- Optimization can either change material choice, processing method, or structural design
  - Designing **the material** for the **application**

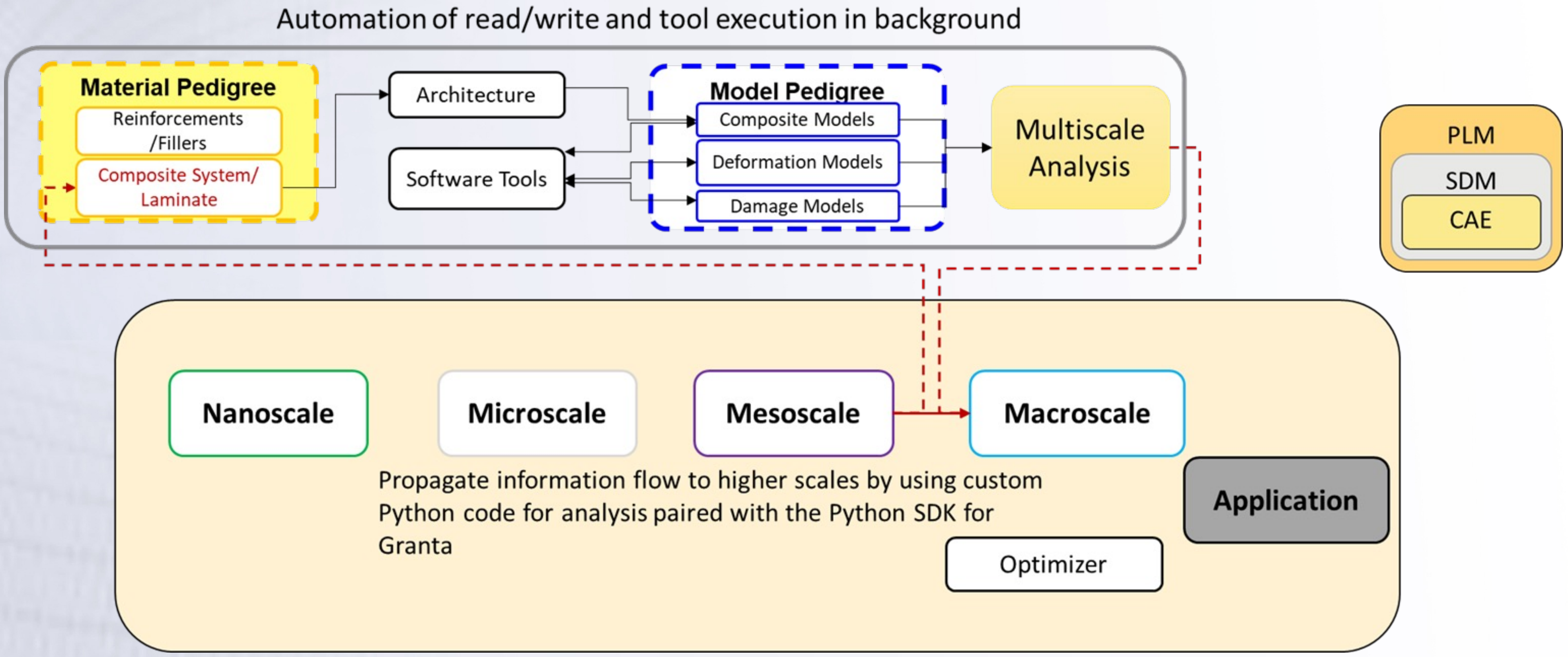
Automation of read/write and tool execution in background





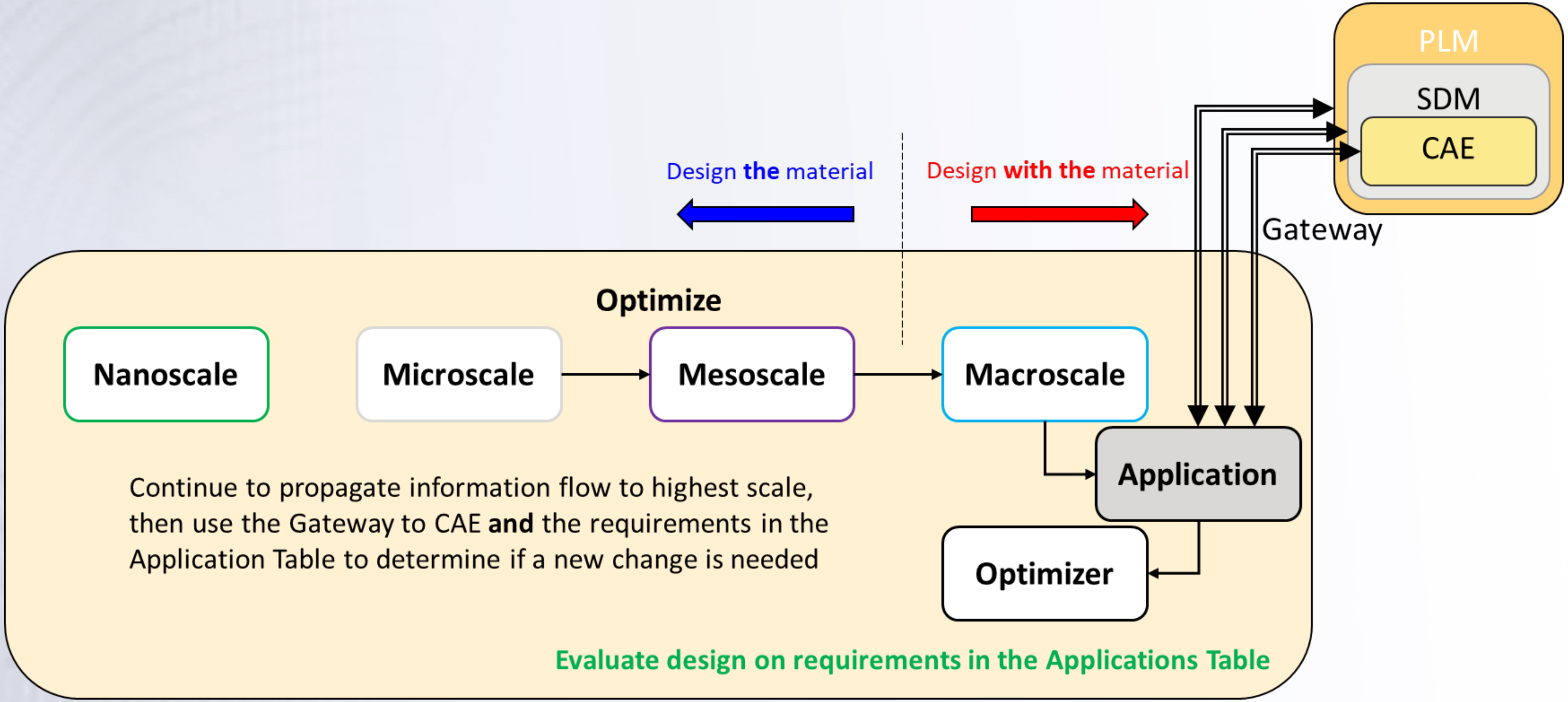
Application Table in Orchestrating ICME

Illustrate with Example in which the **fiber reinforcement of a composite material** used for a structural component is varied



Application Table in Orchestrating ICME

Illustrate with Example in which the **fiber reinforcement of a composite material** used for a structural component is varied



Conclusion/Summary

- ICME enables the design of optimized materials, systems, and manufacturing processes in a concurrent manner
  - Vast improvement over traditional material selection
  - Connects material (design the-material) and structural (design with-the-material) viewpoints
- Application Table ***bridges the gap*** between the two paradigms
  - Provides performance requirements, evaluation criteria, and engineering (geometric, manufacturing etc.) requirements necessary for material/structural design
  - Maintains the digital thread and material digital twins (spatial and temporal property definition)
- Application Table serves a critical role in concurrent ICME optimization for design of "fit-for-purpose" materials and applications
- The Application Table has been **critical missing link** in a robust information system for ICME as it provides the bridge between the material and structural paradigms.

See Arnold S.M, Hearley, B. L., Cebon, D.; "Application Table: A Bridge Connecting the Designing "With-the-Material" and "the-Material" Paradigms", **NASA/TM-20220018403** for more details

Thank You for Your Attention

Integrate Don't Duplicate

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